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Three-Dimensional Linear Analysis of Fluid-Structure Interaction Effects in the Mark I BWR Pressure Suppression Torus

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ABSTRACT

Most analytical and experimental approaches to the evaluation of fluid-structure interaction (FSI) effects in the General Electric Mark I BWR pressure suppression system treat the torus shell as rigid when the shell in real systems is flexible. This report describes linear three-dimensional finite-element analyses of one torus bay that investigated the qualitative effect of torus wall flexibility on hydrodynamic loads induced by a nominal safety relief valve (SRV) discharge. The results of these analyses support the general conclusion drawn from earlier two-dimensional analyses that torus wall flexibility decreases maximum pressures seen by the shell wall, implying that analytical or experimental results obtained for rigid or nearly rigid systems will be conservative when applied to the design of highly flexible real pressure suppression systems. The three-dimensional results also indicate that two-dimensional loads are conservative relative to three dimensions for a given shell thickness.

The report also discusses finite-element analyses of a 3-D representation of the earlier 2-D plane-strain model of the torus shell. Close agreement between the 2-D and 3-D plane-strain results showed that the lower loads predicted by the true 3-D model of the torus bay resulted from the torus geometry and were not an artifact of the particular computer codes used in the analysis.

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The General Electric Mark I boiling water reactor (BWR) pressure suppression system (Fig. 1) consists of a light-bulb-shaped concrete caisson (the "drywell") connected by large pipes to a toroidal steel shell (the "wetwell") partially filled with water. In the case of a hypothetical loss of coolant accident (LOCA), high pressure steam venting from a pipe break within the drywell is injected into the suppression pool where it condenses, maintaining the overpressure of the concrete containment within acceptable structural limits. The pool also serves as a sink for steam periodically discharged from the reactor vessel safety relief valves as a part of normal BWR operation. In either case, the discharge of steam into the pool, together with noncondensible air that is forced ahead of the steam, induces hydrodynamic loads on the suppression torus. Because the suppression torus acts as the primary BWR safety system, a thorough understanding of the hydrodynamic loading of the torus shell is necessary to assure containment integrity under all conditions.

Most analytical and experimental approaches to

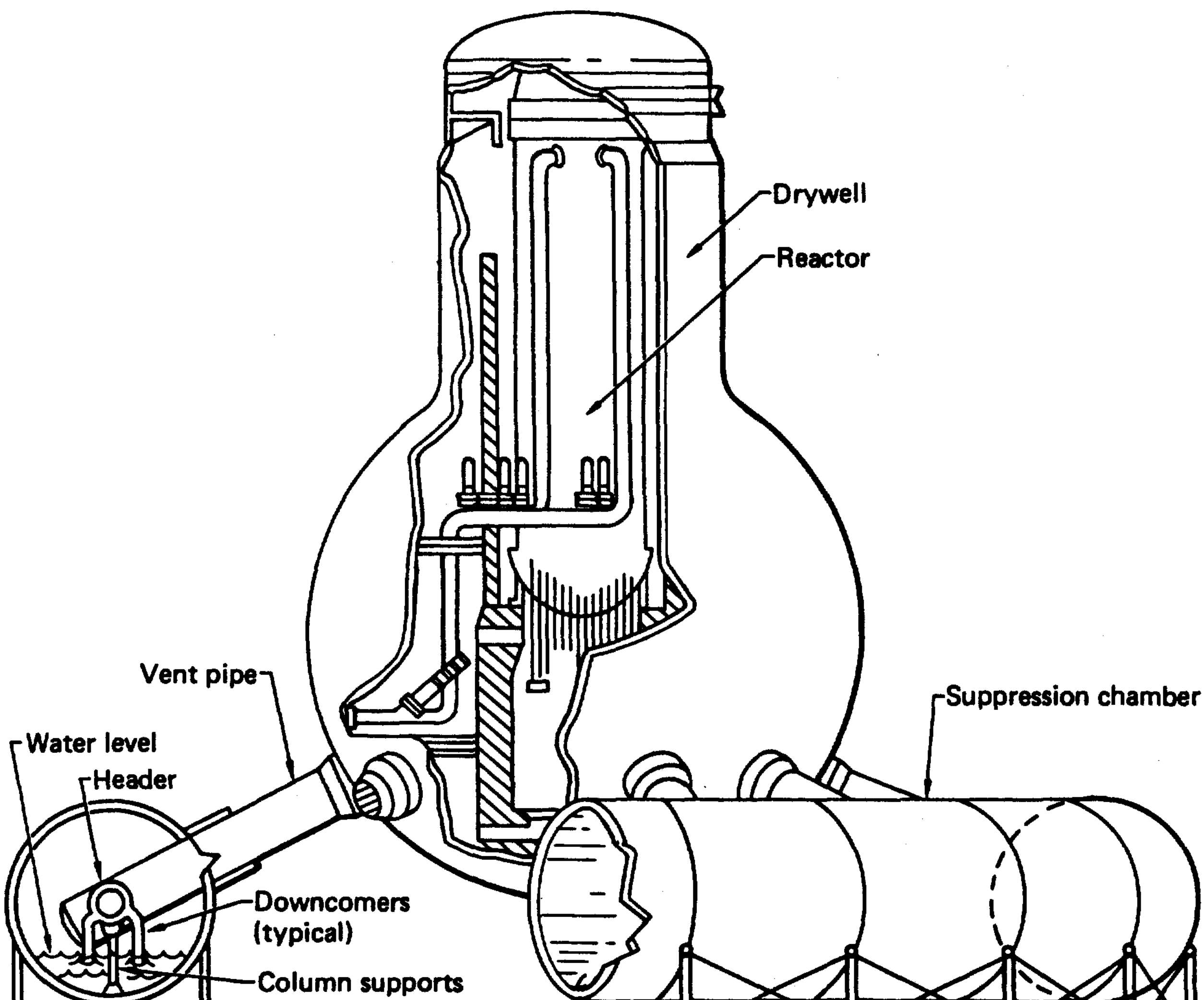

Fig. 1. Overall schematic of the Mark I pressure suppression system.

this problem treat the shell as rigid when, in fact, the shell in real systems is flexible. This article describes linear three-dimensional finite-element analyses that investigated the qualitative effect of torus wall flexibility on hydrodynamic loads induced by a nominal safety relief valve (SRV) air discharge. The results of these analyses support earlier analyses[1] of a two-dimensional finite-element torus model (Fig. 2), conducted using the finite-element computer code DTVIS2, which indicated that attenuation of hydrodynamic loads is enhanced by increasing shell wall flexibility.

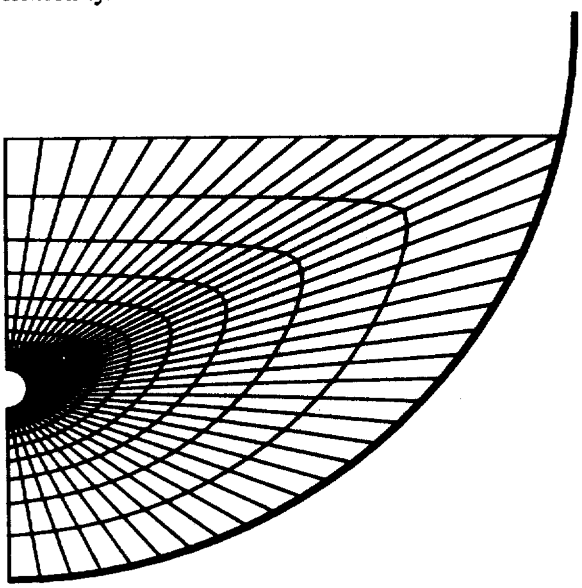

Fig. 2. Two-dimensional SRV torus finite-element mesh.

Three-Dimensional SRV Torus Model

The Mark I pressure suppression torus is actually not a true torus, but instead consists of 16 cylindrical "bays" joined at the ends. The flexibility of the torus shell is characterized by the ratio of shell wall thickness (t) to minor diameter (D) of the torus, with a D/t value of zero denoting absolute rigidity. We completed a series of three-dimensional analyses of one torus bay using the LLL version of the finite-element code SAP4[2] for shell D/t ratios of 0, 300, and 600, corresponding to the shell thicknesses used for the two-dimensional analyses discussed in Ref. 1. The primary dimensions for both models are taken from the Monticello power plant operated by the Northern States Power Company of Minnesota. The Monticello torus D/t is about 580, a value representative of the Mark I containment system.

The analytic model used for the three-dimensional SRV analyses (Fig. 3) is a one-eighth section of a right circular cylindrical shell 421.7 cm in radius

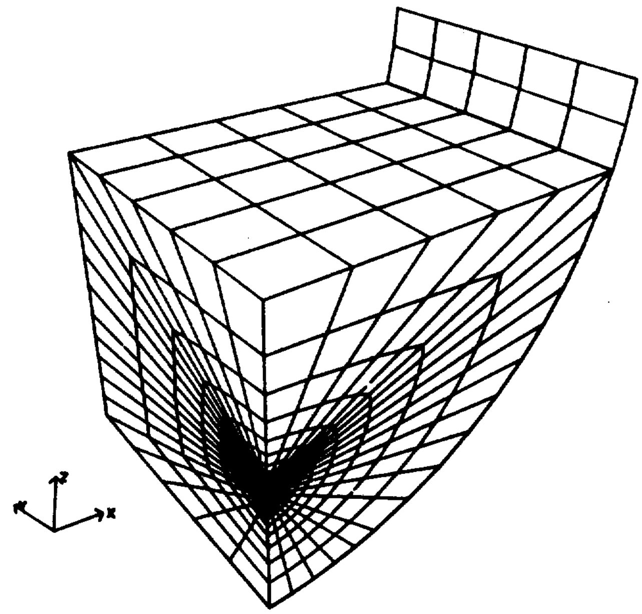

Fig. 3. Three-dimensional SRV torus finite-element mesh.

filled with water to a level 91.4 cm below that of the shell centerline. The "ram's head" SRV discharge header used in the actual system is modeled by a quarter section of a single 25.4-cm-diam bubble, cut by the two planes of symmetry in the problem and located 279 cm below the elevation of the shell centerline. The 22.5-deg angle on the ends of the actual torus bay is neglected to take advantage of symmetry in the problem. Because the radial distance from the bubble center to the end of the bay is significantly greater than that to the pool bottom, the neglect of end effects is assumed to have no effect on the pressure history directly below the bubble during the time period of interest.

The problem uses 1818 nodal points to form the finite-element mesh, yielding 5138 degrees of freedom for the two cases using a flexible shell and 4646 degrees of freedom for the rigid shell case. A total of 1425 eight-node three-dimensional fluid elements is used, 75 of which are defined as "zero shear" elements to simulate the slip condition at the fluid-shell interface. The steel shell is modeled by 85 four-node quadrilateral thin shell elements.

The water is modeled as a nearly incompressible elastic material with a bulk modulus equal to that of water and a trace shear modulus (approximately six orders of magnitude less than the bulk modulus) included to stabilize the problem. (For a more complete description of the fluid modeling, see Ref. 3.) To prevent "locking" and "hour glass" instability in the problem, the bulk and shear terms in the water are integrated separately using one- and two-point quadrature, respectively. In the original three-dimensional SRV model, we did this by defining the fluid elements twice as separate elements classes, one with only a bulk modulus, the other with only shear. In the current model, the fluid elements are defined only once, as modifications in SAP4 allow the separate integration to be executed internally in the code for nearly incompressible problems such as this one.

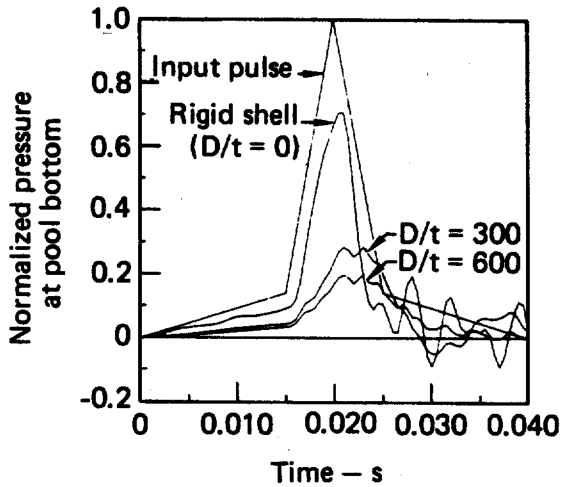

Fig. 4. SRV nominal input pulse with pressure histories calculated at the pool bottom using the DTVIS2 two-dimensional plane-strain model.

The bubble inner surface is loaded by the same 40 ms nominal SRV pulse (Fig. 4) used for the two-dimensional DTVIS2 analyses, divided into 1.0-ms time steps. The theoretical pulse is derived from Rayleigh bubble arguments and has a peak over-pressure of 1.035 MPa. Since the SAP4 code will not directly accept a time-dependent pressure on a surface as input, it was necessary to define load components at each node on the bubble surface corresponding to a unit pressure on the bubble and then multiply these by the pressure function used for the SRV analysis. We defined the load components by the general-purpose mesh generating routine OASIS.[4]

Boundary conditions correspond to those used in the two-dimensional analyses. The shell is rigidly constrained along its upper edge for all cases, and the usual symmetry conditions (i.e., constraint of out-of-plane displacements and rotations) are applied to the xz- and yz-planes indicated in Fig. 3. For the rigid shell case, all nodes defining the shell surface were also locked.

Three-Dimensional Torus Analyses

Results of the three-dimensional torus analyses compared qualitatively with the DTVIS2 plane-strain calculations. Figure 5 shows the pressure history in the fluid at the pool bottom*, normalized to the peak source pressure, that was calculated for shell diameter-to-thickness (D/t) ratios of 0, 300, and 600. As was predicted by the DTVIS2 analyses, the calculated peak pressure decreases with increasing D/t (see Fig. 4), while the pulse shape is broadened and shifted in time as wall flexibility increases. However, the three-dimensionality of the torus problem reduces the magnitude of the peak pressure by as much as a factor of five (see Table 1).

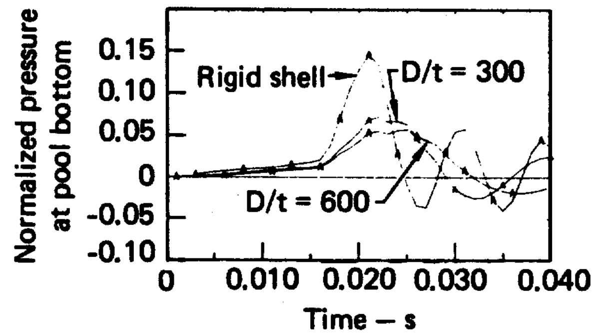

Fig. 5. Pressure response at pool bottom (three-dimensional SRV torus).

Table 1. Comparison of peak pressures[a] predicted at the pool bottom by two- and three-dimensonal SRV analyses.

Shell D/t	Two-dimensional plane-strain	Three-dimensional[b] torus
0	0.70 (1.0)	0.145 (1.0)
300	0.29 (0.41)	0.072 (0.50)
600	0.20 (0.28)	0.057 (0.39)

[a] Pressures are normalized to the peak source pressure (1.035 MPa). Numbers in parentheses indicate pressures normalized to that calculated for the rigid shell by the type of analysis indicated.

[b] Pool bottom in the plane of the bubble.

This result appears reasonable. In the DTVIS2 model, the two-dimensional "bubble" actually represents a cylindrical source of infinite extent, therefore implying an unrealistically large energy input to the problem. The three-dimensional bubble, on the other hand, is a true spherical source. As such, it is significantly less energetic than that in the DTVIS2 model. Furthermore, the three-dimensional torus has an added degree of out-of-plane (i.e., the plane of the

* Except where noted otherwise, the term "pool bottom," when applied to the three-dimensional torus analyses, refers to the bottom of the pool in the plane of the bubble.

bubble) flexibility not treated by the two-dimensional representation. The combined effect of a weaker source and a more flexible shell (for a given D/t ratio) acts to significantly reduce the magnitude of the pressures seen in the torus pool.

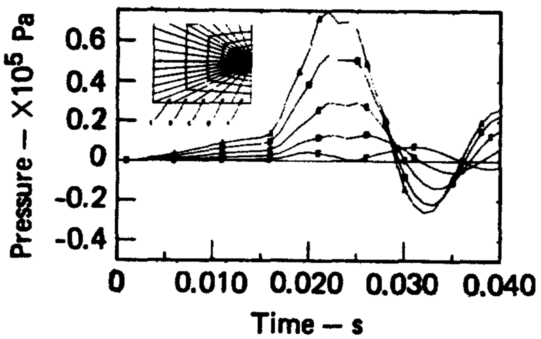

Fig. 6. Pressure histories at indicated locations along the pool bottom.

Peak pressures calculated along the pool bottom at locations not directly beneath the bubble show a marked decrease as axial distance from the bubble plane increases (Fig. 6). Peak pressure at the pool bottom at the end of the torus bay is approximately one order of magnitude less than that in the bubble plane, indicating that the neglect of the 22.5-deg angle on the end of the bay has no apparent effect on the peak pressure calculated in the bubble plane.

Table 1 compares the two- and three-dimensional results. Note that while the absolute magnitudes of the pressures calculated by the torus analyses are significantly lower than those predicted by the planar analyses, the relative magnitudes of the pressures calculated by both the two- and three-dimensional models compare well when each is normalized to the corresponding rigid wall case.

Three-Dimensional Plane-Strain Analyses

To prove an intermediate link between the two- and three-dimensional SRV analyses, the two-dimensional finite-element mesh used with DTVIS2 was expanded to three dimensions and analyzed with SAP4. Three problems were run with this new "slab" mesh, corresponding to the DTVIS2 analyses, for shell D/t ratios of 0, 300, and 600.

A three-element thickness was originally defined for the slab mesh, but this was reduced to one-element layer after a comparison study (using D/t = 300) indicated one-element layer was sufficient for the plane-strain problem. The current slab problem (Fig. 7) uses 1208 nodal points to define a total of 545 three-dimensional fluid elements (including 25 "zero shear" slip elements) and 29 two-dimensional thin shell elements. Model definition (i.e., material properties, bubble loading, etc.) is identical to that used for the three-dimensional SRV torus model.

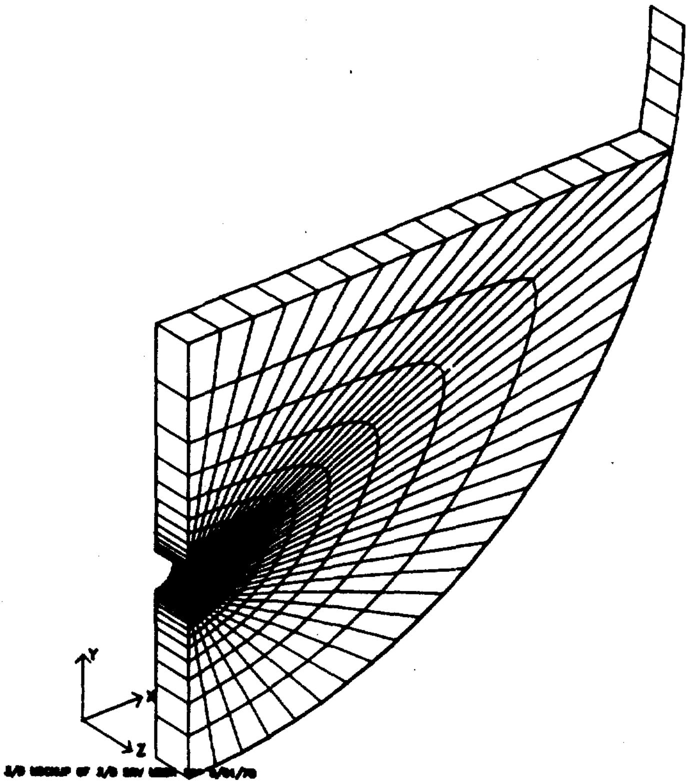

Fig. 7. Three-dimensional slab representation of the DTVIS2 two-dimensional SRV finite-element mesh.

The first comparison between two- and three-dimensional plane strain analyses (using D/t = 300) indicated excellent agreement in both nodal displacements and pressures predicted at the pool bottom; agreement that was consistently repeated between both models at other locations as well. Similar pressure and displacement comparisons were subsequently made between two- and three-dimensional plane-strain analyses for shell diameter-to-thickness ratios of 0 and 600. As indicated in Fig. 8, excellent agreement was again observed between the two model types. The slight discrepancy in peak pressure at the pool bottom predicted for the rigid shell is most likely a result of the fact that the three-dimensional shell rigidity was defined by locking all of the shell nodes absolutely, while shell rigidity in the DTVIS2 model was defined by material properties (i.e., through a very large Young's modulus). The higher peak pressure predicted by the three-dimensional analysis suggests that a trace of wall flexibility is still present in the "rigid" DTVIS2 model.

Because the computer time required to run the three-dimensional slab analyses was about one-tenth of that required for the full SRV torus problems (due

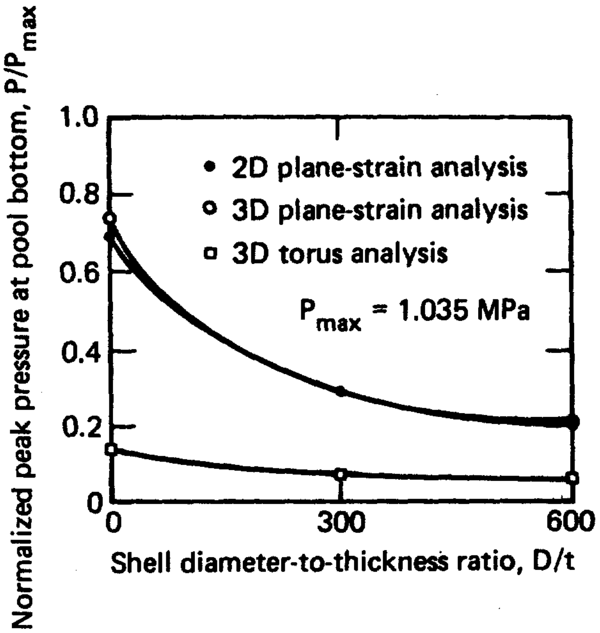

Fig. 8. Comparison of peak pressures calculated at pool bottom by two- and three-dimensional SRV analyses.

primarily to the very small bandwidth of the slab problem), the slab geometry proved valuable as a debugging tool for SAP4 and for the larger torus problem. Through these analyses, we determined, for example, that proper recovery of pressure in the fluid required separate calculation of the hydrodynamic and deviatoric stress components in the fluid elements. The slab analyses also provided a useful check on the method used to define the pressure on the bubble inner surface.

Conclusions

The results of the three-dimensional SRV analyses support the general conclusion drawn from the two-dimensional analyses that torus wall flexibility will decrease the maximum pressures seen by the shell wall. Therefore we can infer that analytical or experimental results obtained for rigid or nearly rigid systems will be conservative when applied to the design of highly flexible real pressure suppression systems. The three-dimensional results further indicate that two-dimensional hydrodynamic loads are conservative relative to three dimensions for a given shell thickness, a conclusion that appears reasonable when the effectiveness of the three-dimensional pool as an energy sink, as well as the added flexibility of the three-dimensional shell, is considered. It is of interest to note, however, that while the magnitudes of the three-dimensional peak pressures are significantly lower than those predicted by the two-dimensional analyses, the relative degree of pressure attenuation with increasing wall flexibility is nearly independent of the type of analysis considered.

It must be emphasized that the results presented here can only be offered as qualitative. Actual quantification of the magnitude of the hydrodynamic attenuation that results from wall flexibility requires more work, particularly including comparisons with experimental data. By such verification activity and by using actual bubble pressure histories as input, a truly realistic analytic assessment of the hydrodynamic loading of the pressure suppression system can be achieved.

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